

SAND REPORT

SAND2005-3583
Unlimited Release
Printed July 2005

Active Polarimeter Optical System Laser Hazard Analysis

Arnold L. Augustoni

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of
Energy under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865)576-8401
Facsimile: (865)576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.doe.gov/bridge>

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone: (800)553-6847
Facsimile: (703)605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/ordering.htm>



SAND2005-3583
Unlimited Release
Printed July 2005

Active Polarimeter Optical System Laser Hazard Analysis

Arnold L. Augustoni
Lasers, Optics & Remote Sensing Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1423

Abstract

A laser hazard analysis was performed for the SNL Active Polarimeter Optical System based on the ANSI Standard Z136.1-2000, American National Standard for Safe Use of Lasers and the ANSI Standard Z136.6-2000, American National Standard for Safe Use of Lasers Outdoors.

Intentionally

Left

Blank

Table of Content

[illegible]

I. Introduction

The Active Polarimeter Optical System (APOS) uses a pulsed, near-infrared, chromium doped lithium strontium aluminum fluoride (Cr:LiSAF) crystal laser in conjunction with a holographic diffuser and lens to illuminate a scene of interest. The APOS is intended for outdoor operations. The system is mounted on a height adjustable platform (6 feet to 40 feet) and sits atop a tripod that points the beam downward. The beam can be pointed from nadir to as much as 60 degrees off of nadir producing an illuminating spot geometry that can vary from circular (at nadir) to elliptical in shape (off of nadir).

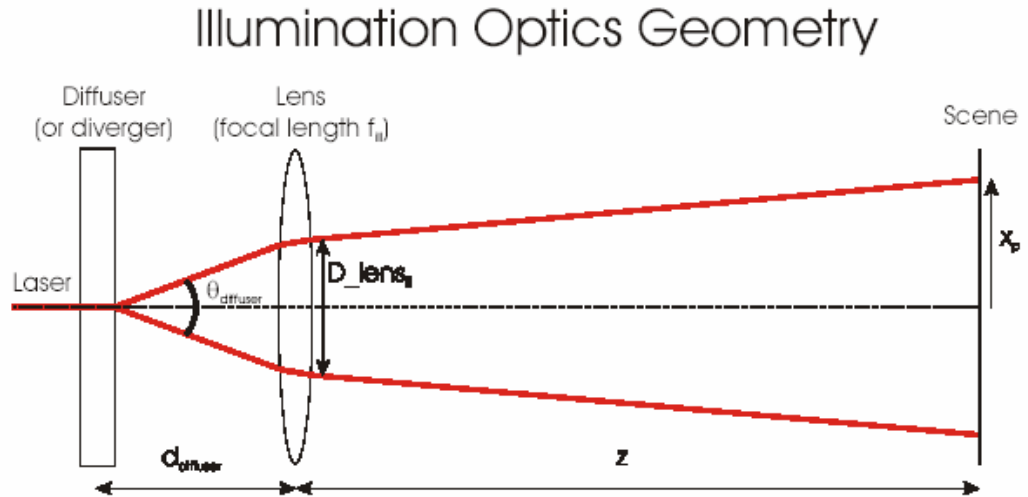


Figure 1

Schematic of the illumination optics geometry.

The JP Innovations crystal Cr:LiSAF laser parameters are presented in *section II*. The illuminating laser spot size is variable and can be adjusted by adjusting the separation distance between the lens and the holographic diffuser. The system is adjusted while platform is at the lowest level. The laser spot is adjusted for a particular spot size at a particular distance (elevation) from the laser by adjusting the separation distance (d_{diffuser}) to predetermined values. The downward pointing

angle is also adjusted before the platform is raised to the selected operation elevation.

II. System Parameters

Laser:-	
Laser Type:	Cr:LiSAF
Manufacturer:	JP Innovation
Model:	3050
Hazard Class:	4
Wavelength:	826 nm
Pulse Energy:	45 mJ
Pulse Duration (FWHM):	122 ns
Pulse Repetition Rate:	30 hertz
Exit Diameter:	2.5 mm
Beam Divergence:	300 microradians
Optical System:-	
Holographic Diffuser Angle:	25°, 40°, 60°
Lens focal length:	10 inch (25.4 cm)
Separation Distance:	$35 \text{ mm} \leq x \leq 140 \text{ mm}$
Polarizer Clear Aperture:	35 mm
Fused Silica Beam Splitter	
Angle:	45°

III. Hazard Analysis

A. Maximum Permissible Exposure

The Maximum Permissible Exposure (MPE) for a pulsed laser is the smallest of the MPE values determined by the application of ANSI Rule 1 through ANSI Rule 3 [*ANSI Std. Z136.1-2000* (8.2.3)].

$$MPE = \min(MPE_{rule1}, MPE_{rule2}, MPE_{rule3})$$

Rule 1 (Single-Pulse MPE)

The formula for the single pulse MPE is given in *ANSI Std. Z136.1-2000* (Table 5a) as:

$$MPE_{rule-1} = 5 \cdot C_A \times 10^{-7} \text{ J/cm}^2 \quad \begin{array}{l} 700 \text{ nm} \leq \lambda < 1050 \text{ nm} \\ 10^{-9} \text{ sec} \leq t < 18 \times 10^{-6} \text{ sec} \end{array}$$

Where the wavelength correction (C_A) as a function of the radiant wavelength (λ) is given in *ANSI Std. Z136.1-2000* (Table 6) as:

$$\begin{aligned} C_A &= 10^{2(\lambda-0.7)} & 700 \text{ nm} \leq \lambda < 1050 \text{ nm} \\ &= 10^{2(0.826-0.7)} \\ &= 10^{0.252} \\ C_A &= 1.79 \end{aligned}$$

The ANSI Rule 1 MPE is evaluated as follows:

$$\begin{aligned} MPE_{rule-1} &= 5 \cdot (1.79) \times 10^{-7} \text{ J/cm}^2 \\ MPE_{rule-1} &= 893 \times 10^{-9} \text{ J/cm}^2 \end{aligned}$$

Rule 2 (Average Power MPE)

$$MPE_{Rule-2} = \frac{MPE_{CW}}{PRF} \quad \text{ANSI Std. Z136.1-2000 (8.2.3-Rule 2)}$$

The standard exposure time for this laser output wavelength is given as 10 seconds [ANSI Std. Z136.1-2000 (Table 4a)].

The appropriate MPE_{CW} for a ten-second exposure is given in Table 5a (ANSI Std. Z136.1-2000) as:

$$MPE_{CW} = C_A \times 10^{-3} \text{ watts/cm}^2 \quad \begin{array}{l} 0.700\mu m < \lambda \leq 1.050\mu m \\ 10 \text{ sec} \leq T \leq 30 \times 10^3 \text{ sec} \end{array}$$

$$MPE_{CW} = 1.79 \times 10^{-3} \text{ watts/cm}^2$$

The appropriate per pulse average power MPE derived from the ANSI Rule 2 is:

$$MPE_{Rule-2} = \frac{1.79 \times 10^{-3} \text{ watts/cm}^2}{30 \text{ sec}^{-1}}$$

The ANSI Rule 2 MPE is:

$$MPE_{Rule-2} = 59.7 \times 10^{-6} \text{ Joules/cm}^2$$

Rule 3 (Multiple-Pulse MPE)

The ANSI Rule 3 MPE is the product of the ANSI Rule 1 MPE and the **multiple pulse correction factor** (C_p) [*ANSI Std. Z136.1-2000 (8.2.3-Rule 3)*].

$$MPE_{Rule-3} = C_p \cdot MPE_{rule1}$$

The **multiple-pulse correction factor** (C_p) – (as a function of the number of laser pulses in the exposure) is given in *Table 6* of the *ANSI Std. Z136.1-2000*.

$$C_p = n^{-0.25}$$

Where “n” is the number of pulses in the exposure (T).

$$n = PRF \cdot T$$

The standard exposure time for this laser’s radiant output wavelength is given as: 10 seconds [*ANSI Std. Z136.1-2000 (Table 4a)*].

$$n = (30 \text{ sec}^{-1}) \cdot (10 \text{ sec})$$

$$n = 300 \text{ pulses}$$

The multiple-pulse correction factor for a 300 pulse exposure is:

$$C_p = (300)^{-0.25}$$

$$C_p = 0.240$$

The appropriate per pulse MPE derived from the ANSI Rule 3 is:

$$MPE_{Rule-3} = (0.24) \cdot (893 \times 10^{-9} \text{ J/cm}^2)$$

Rule 3 MPE is evaluated as follows:

$$MPE_{Rule-3} = 215 \times 10^{-9} \text{ J/cm}^2$$

B. The Appropriate MPE

The appropriate MPE for a pulsed laser is the smallest of the MPE values determined by the application of ANSI Rule 1 through ANSI Rule 3.

Appropriate MPE

ANSI Rule	MPE $\left(\frac{J}{cm^2}\right)$	Comment
1	893×10^{-9}	
2	59.7×10^{-6}	
3	215×10^{-9}	Smallest

C. The Allowable Emission Limit

The Laser Class **Allowable Emission Limit (AEL)** is the highest radiant emission a laser may have and still be considered to be a member of a particular laser hazard class. From the prospective of an observer the AEL may be considered an Allowable Exposure Limit. The Laser Hazard Class 1 AEL is defined as the product of the appropriate MPE and the area associated with the limiting aperture [ANSI Std. Z136.1-2000 (3.2.3.4.1-(2))] and is simply referred to as “AEL”.

$$\text{Class 1 AEL} \equiv MPE \times A_{\text{lim}}$$

The Class 1 AEL for this laser output wavelength is:

$$AEL = MPE \times \frac{\pi}{4} (d_{\text{lim}})^2$$

Where, the limiting aperture for this wavelength is given as 7.0 mm (0.7 cm) [ANSI Std. Z136.1-2000 (Table 8)].

$$AEL = \left(215 \times 10^{-9} \frac{J}{cm^2}\right) \times \frac{\pi}{4} (0.7 \text{ cm})^2$$

$$AEL = \left(215 \times 10^{-9} \frac{J}{cm^2}\right) \cdot (0.385 \text{ cm}^2)$$

$$AEL = 82.6 \times 10^{-9} J$$

D. Laser Safety Eyewear

Eye protection is required where personnel are at risk of ocular exposure to Class 3b or 4 laser hazards [ANSI Std. Z136.1-2000 (4.6.2.1)].

The minimum Optical Density (OD_{\min}) is determined using the maximum radiant laser output (Q_o) through the limiting aperture presented in *Table 8* of the ANSI Std. Z136.1-2000.

$$OD_{\min} = \log\left(\frac{H_o}{MPE}\right) \quad \text{ANSI Std. Z136.1-2000 (4.6.2.5.1)}$$

$$OD_{\min} = \log\left(\frac{Q_o/A_{\lim}}{MPE}\right) = \log\left(\frac{Q_o}{A_{\lim} \cdot MPE}\right)$$

$$OD_{\min} = \log\left(\frac{Q_o}{AEL}\right)$$

$$OD_{\min} = \log\left(\frac{45 \times 10^{-3} J}{82.6 \times 10^{-9} J}\right) = \log(545 \times 10^3)$$

Personnel exposed intrabeam to this laser, within its Nominal Hazard Zone (NHZ) are required to wear laser safety eyewear with a minimum OD of:

$$OD_{\min} = 5.74 \quad @ \quad 826 \text{ nm}$$

E. Nominal Ocular Hazard Distance (No Exit Optics)

The **Nominal Ocular Hazard Distance** (*NOHD*) is the range (R_{NOHD}) to the Safe Eye Exposure Distance (*SEED*). This can also be considered the distance from the laser exit to the boundary of the **Nominal Hazard Zone** (*NHZ*), where the ocular radiant exposure is equal to the MPE. The NOHD is calculated using the formula presented in the appendix of *ANSI Std. Z136.1-2000*.

The NOHD for the JP Innovations, Model 3050 laser (without exit optics) can be evaluated as follows:

$$R_{NOHD} = \frac{1}{\theta} \sqrt{\frac{4Q_o}{\pi MPE} - d^2}$$

Where:

- R_{NOHD} Nominal Ocular Hazard Distance, SEED = NHZ, in centimeters.
- θ Beam divergence, in radians.
- Q_o Radiance (Average Pulse Energy), in Joules.
- MPE Applicable per pulse Maximum Permissible Exposure-intrabeam viewing, in J/cm^2 .
- d Beam diameter at the exit of the laser, in centimeters.

$$R_{NOHD} = \frac{1}{300 \times 10^{-6}} \sqrt{\frac{4(45 \times 10^{-3} J)}{\pi (215 \times 10^{-9} J/cm^2)} - (0.25 cm)^2}$$

$$R_{NOHD} = \frac{1}{300 \times 10^{-6}} \sqrt{\frac{180 \times 10^{-3} cm^2}{\pi (215 \times 10^{-9})} - 0.0625 cm^2}$$

$$R_{NOHD} = 1.72 \times 10^6 cm$$

$$R_{NOHD} = 17.2 km$$

The NOHD for the APOS is variable depending upon the adjusted separation distance between the holographic diffuser and the lens. The NHZ can be restricted to less than the NOHD by the use of approved portable laser barriers set about the laser during laser set up, spot size adjustment and pointing angle adjustment.

F. Spot Size and Radiant Exposure

The holographic diffuser-lens system is used to adjust the APOS output beam for a specific size at a specific distance. For a given platform elevation the spot shape can be varied from a circle (beam point at nadir) to an ellipse (beam point off of nadir). For a particular platform elevation, the smallest beam area (highest radiant exposure) is obtained with a circular spot. The circular beam area presents the “worst case” hazard condition and its use in the laser hazard analysis yields the most conservative safety approach for a particular platform elevation.

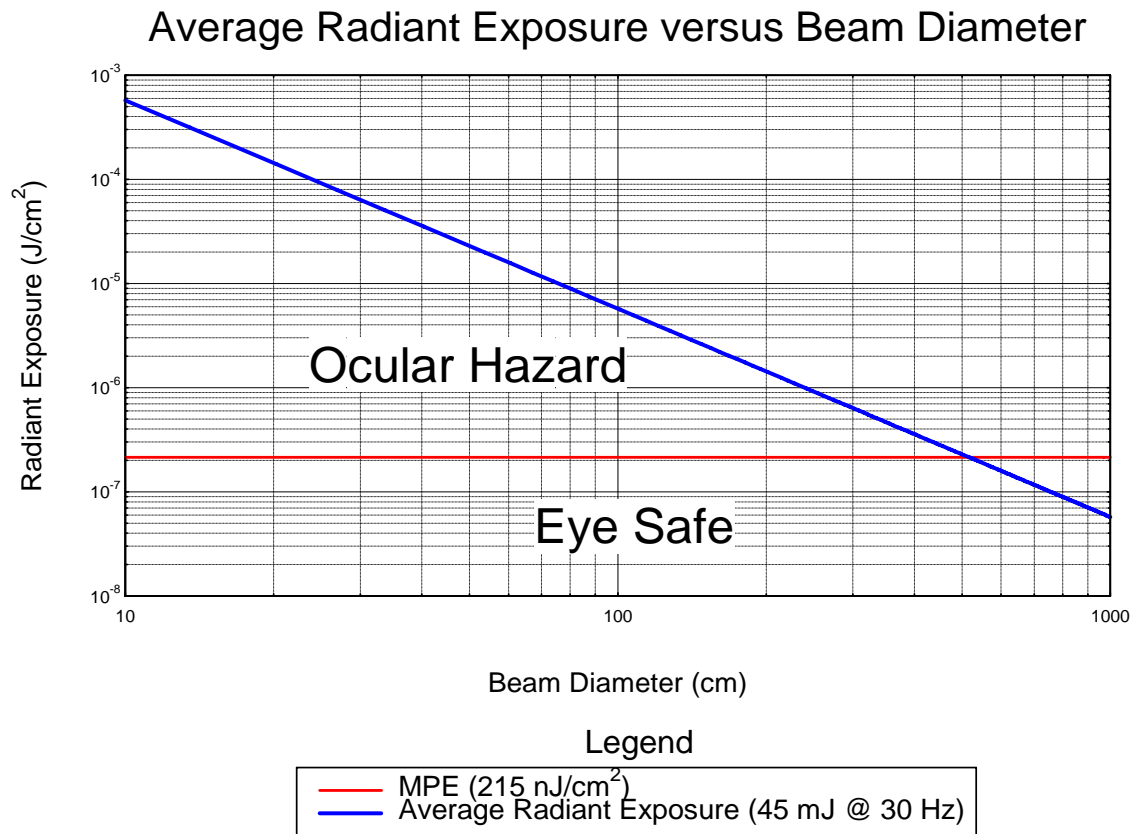


Figure 2

The average radiant exposure above the appropriate MPE presents an ocular hazard to personnel without appropriate eye protection.

The average radiant exposure (\bar{H}) of an assumed circular beam, as a function of the radiant output (Q_o) and spot diameter (D) can be expressed as:

$$\overline{H} = \frac{Q_o}{A} = \frac{Q_o}{\pi \frac{(D)^2}{4}} = \frac{4 \cdot Q_o}{\pi \cdot D^2}$$

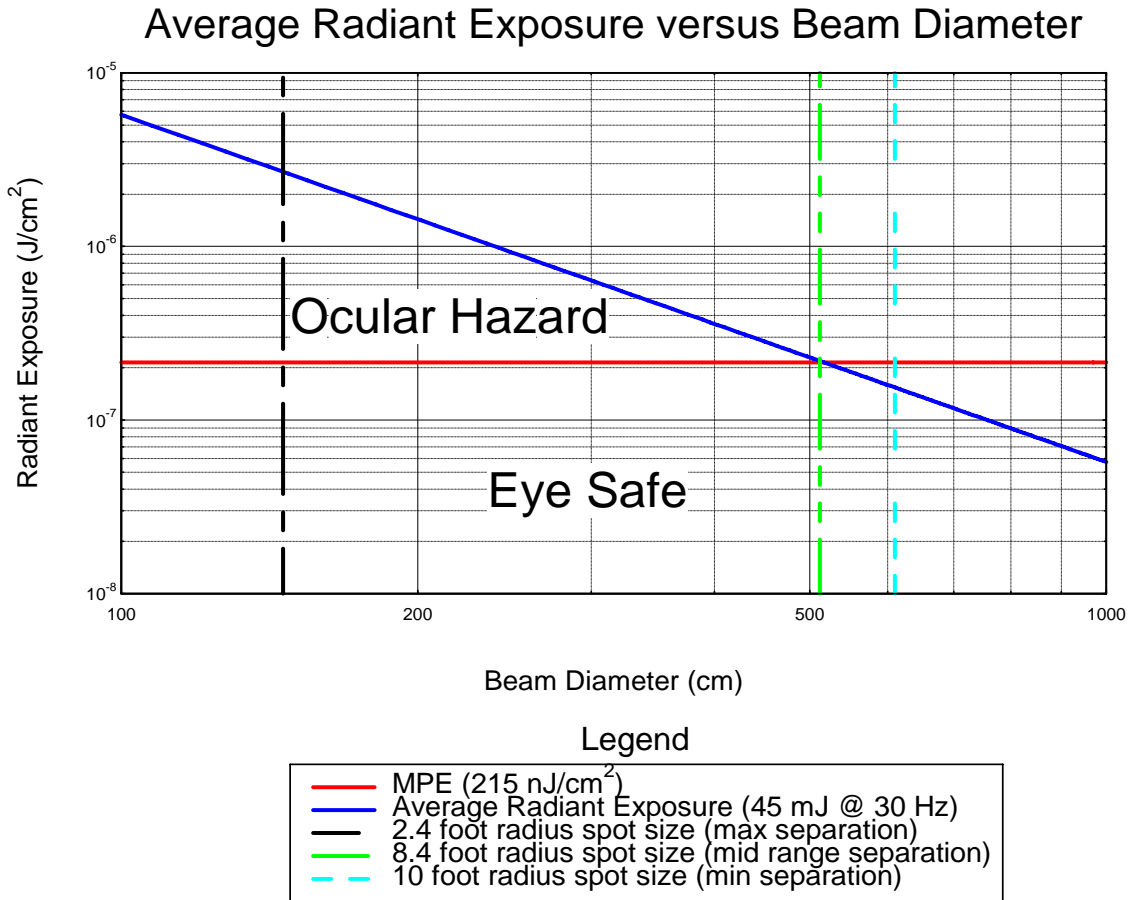


Figure 3

The average radiant exposure for the 2.4 foot radius, 8.4 foot radius and 10 foot radius spot sizes in relation to the MPE. Spot sizes greater than 8.5 feet in radius present eye safe radiant exposure to this the Active Polarimeter Optical System.

The APOS illumination spot size is determined by the separation distance between the holographic diffuser and the lens (ranging from 35 mm to 150 mm), which is nominally set at 70 mm and the distance from the laser, which varies from a minimum of 6 feet at nadir to a maximum of 80 feet at the maximum elevation (40 feet) and a pointing angle of 60-degrees off of nadir. The circular

illuminating spot sizes are expected to range from as small as 2.4 feet in radius to ten feet in radius.

The minimum circular beam radius (R_{MPE}) necessary to produce an “eye safe” radiant exposure ($H_{eye-safe}$) to this laser can be determined as follows;

$$H_{eye-safe} = \frac{Q_o}{A_{MPE}} = MPE$$

$$A_{MPE} = \frac{Q_o}{MPE} = \frac{\pi}{4} (D_{MPE})^2$$

$$A_{MPE} = \frac{Q_o}{MPE} = \frac{\pi}{4} (2 \cdot R_{MPE})^2$$

$$R_{MPE} = \frac{1}{2} \sqrt{\frac{4 \cdot Q_o}{\pi \cdot MPE}}$$

$$R_{MPE} = \frac{1}{2} \sqrt{\frac{4 \cdot (45 \times 10^{-3} J)}{\pi \cdot (215 \times 10^{-9} J/cm^2)}}$$

$$R_{MPE} = 258.11 \text{ cm} \cdot \left(\frac{1 \text{ inch}}{2.54 \text{ cm}} \right) \cdot \left(\frac{1 \text{ foot}}{12 \text{ inches}} \right)$$

The minimum “eye safe” spot radius for this laser is:

$$R_{MPE} = 8.47 \text{ feet}$$

For illumination circular spot radii greater than $8 \frac{1}{2}$ feet the radiant exposure from this laser is below the ocular MPE and can be considered eye safe.

G. Outdoor Operations and Navigable Air Space

The radiant output wavelength (826 nm) of the APOS is outside the visible portion of the spectrum as defined by *ANSI Std. Z136.1-2000*^{*}, and *ANSI Std. Z136.6-2000*[†] and does not pose a visual interference (distraction, disruption, or disorientation) concern for aircrews in navigable air space. Startle, dazzle, flashblindness and glare concerns apply only to visible light and do not apply to invisible laser beams. The critical zone exposure distances (*CZED*) and the sensitive zone exposure distance (*SZED*) do not apply.

The NOHD (for invisible as well as visible laser light) does apply in the Normal Flight Zone (*NFZ*). The NOHD of the JP Innovations lasers was determined to be as great as 17.3 kilometers without the APOS exit optic system. Care shall be taken not to direct the APOS output beam into navigable air space.

For the normal operation of the APOS, the beam is directed toward the ground from an elevated platform. Care should be taken to avoid specular reflections which may re-directed the laser output into navigable air space.

H. Aided Viewing

The use of optical aides such as a pair of 7x50 binoculars for intrabeam viewing will increase the viewing hazard by as much as the square of the magnifying power (optical gain) of the optical system [*ANSI Std. Z136.1-2000 (B6.4.3)*].

The actual gain of the optical system considers the transmission factor to the optical system.

$$G = \tau_{\lambda} \left[\frac{D_o}{D_e} \right]^2 = \tau_{\lambda} P^2$$

Where;

- G : Optical Gain
- P : Magnifying Power
- D_o : Diameter of objective optic
- D_e : Diameter of exit pupil
- τ_{λ} : Transmission factor of the optical system

^{*} Visible: $400 \text{ nm} \leq \lambda \leq 700 \text{ nm}$,

[†] Visible: $380 \text{ nm} \leq \lambda \leq 780 \text{ nm}$

The actual gain of a 7x50 binocular exposure to 826 nm laser light can be calculated from the transmission loss given in Table 9 of the ANSI Std. Z136.1-2000 and as:

$$G = (0.7) \left[\frac{50 \text{ mm}}{7 \text{ mm}} \right]^2$$

$$G = 35.7$$

The use of optical aides extends the ocular hazard distance associated with this laser. This Extended Ocular Hazard Distance (EOHD) is related to the NOHD by the inclusion of the optical gain factor as follows:

$$R_{EOHD} = \frac{1}{\theta} \sqrt{\frac{4 \cdot G \cdot Q_o}{\pi \text{ MPE}}} - d^2$$

For a first order approximation this EOHD can be expressed as:

$$R_{EOHD} \approx \sqrt{G} \cdot R_{NOHD}$$

$$R_{EOHD} \approx 6 \cdot R_{NOHD}$$

The use of 7x50 binocular extends the NHZ by an approximate factor of six. The use of optical aides should be greatly restricted during APOS laser operations.

IV. Conclusions

1. Personnel inside the Nominal Hazard Zone (NHZ), with the laser active, are required to wear laser safety eyewear with a minimum Optical Density (OD) of 5.74 at 826 nm.
2. Barriers (temporary or permanent) about the laser are required to confine and reduce the NHZ, from approximately 17.2 kilometers to a more manageable distance (from the laser) that can be controlled during laser setup and spot size and pointing angle adjustment process.
3. While the laser illuminating spot sizes greater the 8.5 feet in radius produce eye safe radiant exposures; it is required that laser safety eyewear be worn by all personnel throughout the laser setup, spot size adjustment, positioning and testing process to prevent inadvertent radiant exposures above the MPE with a possible ocular injury.
4. Although the APOS laser beam does not pose a visual interference (distraction, disruption, or disorientation) concern for aircrews in navigable air space; the NOHD does apply. Care shall be taken to avoid directing the APOS beam into navigable air space. Care should be taken to avoid specular reflections into navigable air space.
5. The use of optical viewing aides such as 7x50 binoculars extends the nominal hazard distance by an approximate factor of six and should not be allowed during APOS laser operations.

V. Reference

ANSI Std. Z136.1-2000: for Safe Use of Lasers, Published by the Laser Institute of America.

ANSI Std. Z136.6-2000: for Safe Use of Lasers Outdoors, Published by the Laser Institute of America.

FAA Order 7400.2E Chapter 29: Outdoor Laser Operations

VI. Distribution

# of copies	MS	Name
5	1423	Arnold L. Augustoni, 01128
1	1423	Gregory Hebner, 01128
3	0570	Eric A. Shields, 05712
3	0570	Bridget K. Ford, 05712
1	0570	Craig M. Boney, 05712
2	1094	Michael C. Oborny, 06327
1	0870	Chad E. Hjorth, 06327
1	9018	Central Technical Files, 8945-1
2	0899	Technical Library, 9616